

## Suborbital Measurements of Spectral Aerosol Optical Depth and Its Variability at Subsatellite Grid Scales in Support of CLAMS 2001

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### ABSTRACT

As part of the Chesapeake Lighthouse and Aircraft Measurements for Satellites (CLAMS) experiment, 10 July–2 August 2001, off the central East Coast of the United States, the 14-channel NASA Ames Airborne Tracking Sunphotometer (AATS-14) was operated aboard the University of Washington's Convair 580 (CV-580) research aircraft during 10 flights (~45 flight hours). One of the main research goals in CLAMS was the validation of satellite-based retrievals of aerosol properties. The goal of this study in particular was to perform true over-ocean validations (rather than over-ocean validation with ground-based, coastal sites) at finer spatial scales and extending to longer wavelengths than those considered in previous studies. Comparisons of aerosol optical depth (AOD) between the Aerosol Robotic Network (AERONET) Cimel instrument at the Chesapeake Lighthouse and airborne measurements by AATS-14 in its vicinity showed good agreement with the largest  $r$ -square correlation coefficients at wavelengths of 0.38 and 0.5  $\mu\text{m}$  ( $>0.99$ ). Coordinated low-level flight tracks of the CV-580 during *Terra* overpass times permitted validation of over-ocean Moderate Resolution Imaging Spectroradiometer (MODIS) level 2 (MOD04\_L2) multi-wavelength AOD data (10 km  $\times$  10 km, nadir) in 16 cases on three separate days. While the correlation between AATS-14 and MODIS-derived AOD was weak with an  $r$  square of 0.55, almost 75% of all MODIS AOD measurements fell within the prelaunch estimated uncertainty range  $\Delta\tau = \pm 0.03 \pm 0.05\tau$ . This weak correlation may be due to the small AODs (generally less than 0.1 at 0.5  $\mu\text{m}$ ) encountered in these comparison cases. An analogous coordination exercise resulted in seven coincident over-ocean matchups between AATS-14 and Multiangle Imaging Spectroradiometer (MISR) measurements. The comparison between AATS-14 and the MISR standard algorithm regional mean AODs showed a stronger correlation with an  $r$  square of 0.94. However, MISR AODs were systematically larger than the corresponding AATS values, with an rms difference of ~0.06. AATS data collected during nine extended low-level CV-580 flight tracks were used to assess the spatial variability in AOD at horizontal scales up to 100 km. At UV and midvisible wavelengths, the largest absolute gradients in AOD were 0.1–0.2 per 50-km horizontal distance. In the near-IR, analogous gradients rarely reached 0.05. On any given day, the relative gradients in AOD were remarkably similar for all wavelengths, with maximum values of 70% (50 km)<sup>-1</sup> and more typical values of 25% (50 km)<sup>-1</sup>. The implications of these unique measurements of AOD spatial variability for common validation practices of satellite data products and for comparisons to large-scale aerosol models are discussed.

### 1. Introduction

The Chesapeake Lighthouse and Aircraft Measurements for Satellites (CLAMS) campaign was a clear-sky, shortwave (SW) closure campaign and entailed measurements from the Chesapeake Lighthouse research platform [hereafter called COVE [the Clouds and the Earth's Radiant Energy System (CERES)

Ocean Validation Experiment]], several land sites, six research aircraft, and the *Terra* satellite (Smith et al. 2005). CLAMS research goals included validation of satellite-based retrievals of aerosol properties and vertical profiles of radiative fluxes, temperature, and water vapor. Suborbital measurements of aerosol optical depth (AOD) and columnar water vapor (CWV) were carried out at several Aerosol Robotic Network (AERONET) sites (Holben et al. 1998) and aboard five of the six airborne platforms using a variety of techniques. The University of Washington's Convair 580 (CV-580) research aircraft carried a suite of in situ instruments to characterize aerosol properties and the ambient radiation field (Magi et al. 2005). Among the remote sensors aboard the CV-580 was the National

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Aeronautics and Space Administration (NASA) Ames Airborne Tracking Sunphotometer (AATS-14), which measures direct solar beam transmission through the atmosphere to determine AOD between 0.354 and 1.558  $\mu\text{m}$ , as well as columnar water vapor.

Spaceborne satellite sensors offer many potential advantages for studying aerosols at regional to global scales (Kaufman et al. 2002; Ramanathan et al. 2001). Among the sensors that have provided global aerosol information in the past are the Advanced Very High Resolution Radiometer (AVHRR) and the Total Ozone Mapping Spectrometer (TOMS), even though they were not optimized for the detection of aerosols. With the launch of the Earth Observing Satellite (EOS) *Terra* in 1999, a new era of satellite-based observations of aerosols began. The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard *Terra* and *Aqua* (Kaufman et al. 1997) and the Multiangle Imaging Spectroradiometer (MISR) instrument (Diner et al. 1998; Martonchik et al. 1998) aboard *Terra* strive for improved radiometric calibration and are much more capable of detailed global aerosol observations. In the case of the MODIS instrument, for example, the advantages of the new sensor include its improved spectral coverage, the narrower bandwidth of the individual channels, and improved spatial resolution of 500 m (250 m for some channels, compared to 1 or 4 km for AVHRR and 50 km for TOMS). For MISR, the improved capabilities further stem from its multiangle viewing technique, which results in the ability to separate surface from atmospheric properties and provides sensitivity to particle shape. In particular, the improved spatial resolution of the new sensors allows for a better detection and identification of clouds and hence an improved separation of aerosols from clouds.

Of considerable interest to satellite-based retrievals of aerosol optical depth is small-scale (a few hundred meters or less) variability. The question arises whether an average radiance in a given scene, as measured by a satellite sensor, can be readily translated into an average AOD over the scene. For example, in preliminary validation studies of the standard MISR AOD retrieval algorithm, Kahn et al. (2001a) found that over dark water, pixel-to-pixel scene variability could contribute more to the aerosol optical depth retrieval uncertainty than uncertainties in the calibration of the MISR cameras. In the case of MODIS, spatial variability is of equally high importance. Both the MODIS over-ocean and over-land aerosol retrieval algorithms depend heavily on the spatial variability of radiances and hence also on the variability of aerosol fields in order to detect and mask cloudy pixels (Remer et al. 2005). In the case of the land algorithm, the standard MODIS cloud mask may discard pixels that contain increased AOD in the immediate vicinity ( $<500$  m) of clouds. Also, the aerosol retrieval algorithm discards those pixels that have sufficient cloud contamination to place them in the upper 50% in terms of their reflectance at 0.66  $\mu\text{m}$ . In the

case of the ocean algorithm, cloud masking is based solely on the spatial variability of the reflectance at 0.55  $\mu\text{m}$  (Martins et al. 2002). Hence, suborbital measurements of the actual spatial variability of AOD and tests of the impact of that variability on satellite radiances are crucial in assessing the adequacy of the aerosol retrieval algorithms and the cloud-screening procedures used within them.

Spatial variability on the scale of a few hundred meters can only be assessed from suborbital platforms that move fast by comparison to wind advection speeds, and only with instruments that provide data at rates of a few hertz (1 Hz being equivalent to a spatial resolution of  $\sim 100$  m at an aircraft speed of  $\sim 200$  kt or  $103$  m  $\text{s}^{-1}$ ). Current airborne lidars are generally backscatter systems and as such deliver only limited qualitative information on aerosol variability, since the inversion of a backscatter lidar signal requires a priori knowledge of the extinction-to-backscatter (lidar) ratio (Klett 1985). When deployed on a fast-moving aircraft such as the CV-580 during CLAMS, the NASA Ames Airborne Tracking Sunphotometers (AATS-6 and AATS-14) on the other hand provide the spatial resolution, data acquisition speed, and accuracy to support the overall goals of CLAMS and other satellite validation studies. Because the AATS instruments measure the direct solar beam transmission, and are hence unaffected by surface properties, they are excellent tools for studying the spatial variability of AOD and columnar water vapor on scales of a few hundred meters. By comparison to satellite observations, however, the AATS measurements lack the advantage of an instantaneous data collection.

In this paper, we describe the AATS-14 measurements of AOD during the CLAMS experiment, with a special emphasis on assessing the spatial variability of AOD on subsatellite grid scales with a resolution of  $\sim 100$  m. We include validation measurements for the MODIS and MISR over-ocean AOD retrieval products. For MISR, the standard aerosol retrieval algorithm produces results for a grid of  $16 \times 16$  pixels ( $17.6$  km  $\times$   $17.6$  km), while the most relevant grid size for MODIS validation efforts has been  $5 \times 5$  level 2 boxes, resulting in a grid of  $50$  km  $\times$   $50$  km at nadir. Hence, we assess AATS-14-derived AOD variability at and below these spatial scales, determining both the mean AOD at these scales as well as the maximum variability within the satellite grids. In addition, we present comparisons of AOD measurements by the airborne AATS-14 and by an AERONET Cimel sun photometer stationed at the COVE platform ( $36.9^\circ\text{N}$ ,  $75.71^\circ\text{W}$ ). We also analyze the AOD variability in the vicinity of the COVE site. In this way we assess the suitability of the COVE platform as a satellite validation site and support one of the overall goals of the CLAMS experiment, namely, to determine how representative measurements at the COVE site may be of the satellite grids around it.